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Radiation characteristics of two-element array of equilateral triangular patch microstrip antenna in plasma medium

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Abstract : The far zone EM-mode and P-mode radiation fields are derived using vector wave function techniques and pattern multiplication approaches. An analytical study of a two-element array of equilateral triangular patch microstrip antenna is presented at a frequency of 10 GHz. The results are obtained both in plasma medium and in free space and compared with those of single-element triangular patch microstrip antenna. Some important antenna parameters such as radiation conductance, radiation efficiency, directivity and quality factor are plotted for different values of plasma to source frequency. It is observed that EM-mode field patterns are modified to a great extent, where as the P-mode field patterns show discrete ray-like structure similar to single element triangular patch microstrip antenna.

Keywords : Microstrip array antenna, radiation properties, plasma.

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1. Introduction

Microstrip patch antennas and their arrays have been the centre of attention in the past decades due to their exclusive merits such as light weight, flat profile, low manufacturing cost and compatibility with integrated circuits [1–4]. These antennas are becoming popular in many communication systems for aerospace vehicles, satellites and other systems.

Microstrip antennas mounted on such aerospace vehicles encounter plasma medium during their travel in space, as a result of which radiation properties are altered significantly. This change is caused due to generation of electroacoustic waves in addition to electromagnetic waves.

Saxena and Gupta [5] have obtained expressions for the far zone EM-mode and the P-mode component of radiation fields for a single-element triangular patch microstrip antenna in a warm, homogeneous and isotropic plasma medium. In the present paper, the same work has been extended for a two-element microstrip array antenna.

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2. Radiation field expressions

The top and side view of configuration of array antenna is shown in Figure1. It consists of two identical triangular microstrip patch elements of arm length a, on a dielectric substrate of thickness h and substrate permittivity ε_r. The array elements are separated by a distance d and the

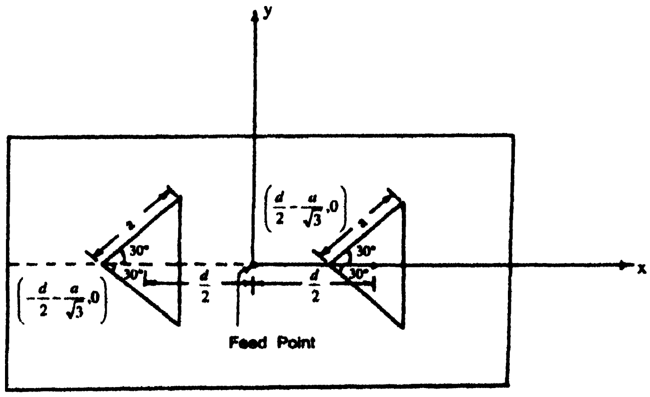

Figure 1(a). 2D-Top view of configuration of two-element triangular patch microstrip array antenna.

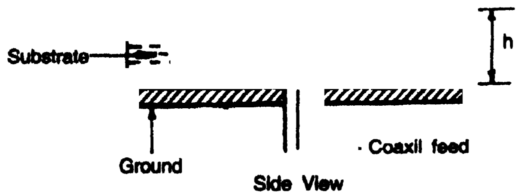

Figure 1(b). Side view of configuration of two-element triangular patch microstrip array antenna.

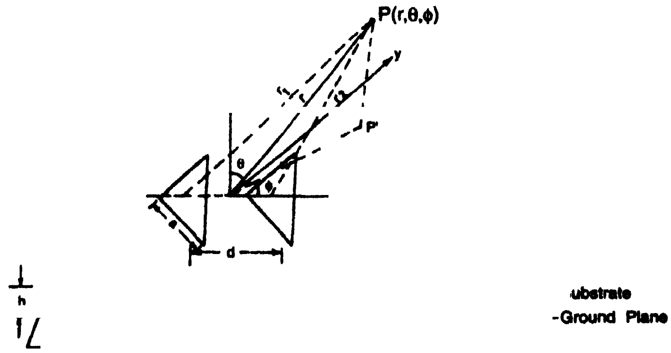

Figure 1(c). 3D view of configuration of two-element triangular patch microstrip array antenna.

progressive phase excitation difference between the patches is β_1. Each patch can be excited by a microstrip transmission line connected to the edge or by a coaxial line from the back at the plane $\phi = 0$. Several investigators [5,6] have considered the patch as a cavity which acts as a disc resonator. We have considered TM_{nm} mode with respect to Z-axis. Here, n and m are the mode numbers associated with X and Y directions respectively.

The E_z component of field inside the cavity for dominant mode is given as

$$E_z = A_{1,0,-1}[2\cos(2\pi x/\sqrt{3}a + 2\pi/3).\cos(2\pi y/3a) + \cos(4\pi y/3a)]. \tag{1}$$

Other field component are obtained by solving Maxwell's equations. By image theory, the ground plane may be replaced by an image of the top conductor.

The magnetic currents also exist along the edges of triangular conductor and may be evaluated from :

$$\boldsymbol{M} = 2(\boldsymbol{E} \times \boldsymbol{n}). \tag{2}$$

where $\boldsymbol{n}$ is a unit vector normal to the aperture.

Using linearized hydrodynamic theory of plasma, vector wave function technique and neglecting the coupling between the elements [6,7], the far-zone fields of the two-element array of triangular microstrip patch antenna are given as

$$E_{\theta t} = -\mathrm{i}\eta_0\omega_0.\{-F_x\sin\phi + F_y\cos\phi\} \times \left[\frac{\exp.\{-\mathrm{i}(\beta_e r_1 + 0.5\beta_1)\}}{r_1} + \frac{\exp\{-\mathrm{i}(\beta_e r_2 - 0.5\beta_1)\}}{r_2}\right], \tag{3}$$

$$E_{\theta t} = -\mathrm{i}\eta_0\omega_0.[F_x\cos\theta\cos\phi + F_y\cos\theta\sin\phi] \; . \; \exp.\{-\mathrm{i}(\beta_e r_1 + 0.5\beta_1)\} + \exp\{-\mathrm{i}(\beta_e r_2 - 0.5\beta_1)\} \tag{4}$$

In the far zone field region, the value of radius vector r_1, r_2 can be calculated from the Figure 1.

$r_1 \approx r + d/2.\cos\theta$,

$r_2 \approx r - d/2.\cos\theta$, for phase variation and

$r_1 \approx r_2 \approx r$, for amplitude variation.

Applying these approximations in eqs. (3) and (4), we get :

EM-mode :

$$E_{\theta t} = -\mathrm{i}\,\eta_0\omega_0.[-F_x.\sin\phi + F_y.\cos\phi]. \times 2\cos[0.5(\beta_e.d.\cos\theta + \beta_1)].\frac{e^{-i\beta er}}{r} \tag{5}$$

$$E_{\phi t} = -\mathrm{i}\,\eta_0\omega_0.[-F_x.\cos\theta\sin\phi + F_y.\cos\theta\sin\phi]. \times 2\cos[0.5(\beta_e.d.\cos\theta + \beta_1)].\; e^{-i\beta er} \tag{6}$$

and

P-mode :

$$E_{pt} = 2h\omega_p^2/3a\omega_0\varepsilon_0(\omega_0^2 - \omega_p^2) \times \exp(-\mathrm{i}\beta_p r)/r \times \exp(-\mathrm{i}\beta_p a\sin\theta\cos\phi/\sqrt{3}) \times 2\cos[0.5(\beta_p d\,\cos\theta + \beta_1) \times [E_{px} + E_{py}]. \tag{7}$$

where, $E_{\theta t}$, $E_{\phi t}$ = component of total electric field vectors for EM-mode, E_{pt} = total electric field vector for P-mode, Fx = x-component of vector electric potential, F_y = y-component of vector electric potential, E_{px} = x-component of electric field vector for P-mode, E_{py} = y-component of electric field vector for P-mode, β_e = phase propagation constant for EM-mode given by $2\pi A/\lambda_0$, β_p = phase propagation constant for P-mode given by $\beta_e c/v$, c = velocity of light, v = root mean square thermal velocity of electron, A = plasma frequency parameter given by $(1 - \omega_p^2/\omega_0^2)^{1/2}$, ω_p = angular plasma frequency, ω_0 = angular source frequency, β_1 = the progressive phase excitation difference between the patches.

3. Field patterns

The expression for total field pattern $R(\theta,\phi)$ is obtained as

$$R(\theta,\phi) = |E_{\theta t}|^2 + |E_{\phi t}|^2 . \quad (8)$$

Then, the radiation field patterns in the E-plane ($\phi = 0$) and H-plane ($\phi = \pi/2$) are given as :

$$R_e(\theta,\phi) = |E_{\theta t}|^2 + |E_{\phi t}|^2 = \eta_0^2\omega^2 0.(|F_y|^2 + |F_x|^2.\cos^2\theta), \quad \text{(E-plane)}, \quad (9)$$

$$R_h(\theta,\phi) = |E_{\theta t}|^2 + |E_{\phi t}|^2 = \eta_0^2\omega^2{}_0.(|F_x|^2 + |F_y|^2.\cos^2\theta), \quad \text{(H-plane)}. \quad (10)$$

The values of R_e and R_h are calculated for a case taking f =10 GHz, a = 1.1 cm, d =1.5 cm, n = 1, ε_r =3.55 and the phase difference $\beta_1 = \pi/2$. The results are plotted in Figures 2 and 3 respectively for two different planes (ϕ = 0 and $\phi = \pi/2$) for A = 0.5 *i.e.* in plasma and A = 1.0 *i.e.* in free space. The P-mode fields are plotted in Figure 4 for A = 0.5 for a limited range of 10° (from 50° to 60°). The field pattern are also compared with single-element triangular patch microstrip antenna.

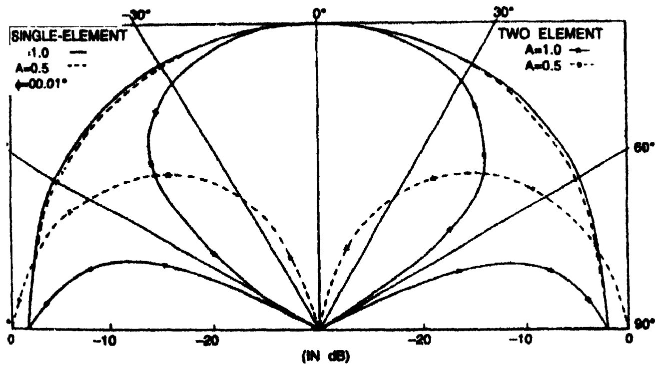

Figure 2. Variation of $R_e(\theta,\phi)$ for A =1.0 (free space) and A = 0.5 (plasma), for single-element and two-element ($\beta_1 = \pi/2$) equilateral triangular patch microstrip antenna.

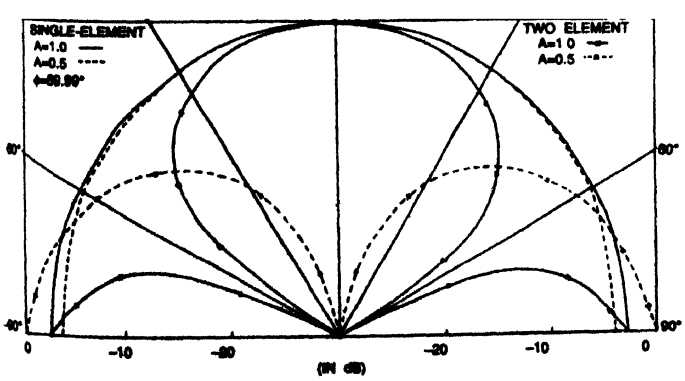

Figure 3. Variation of $R_h(\theta,\phi)$ for A = 1.0 (free space) and A = 0.5 (plasma), for single-element and two-element ($\beta_1 = \pi/2$) equilateral triangular patch microstrip

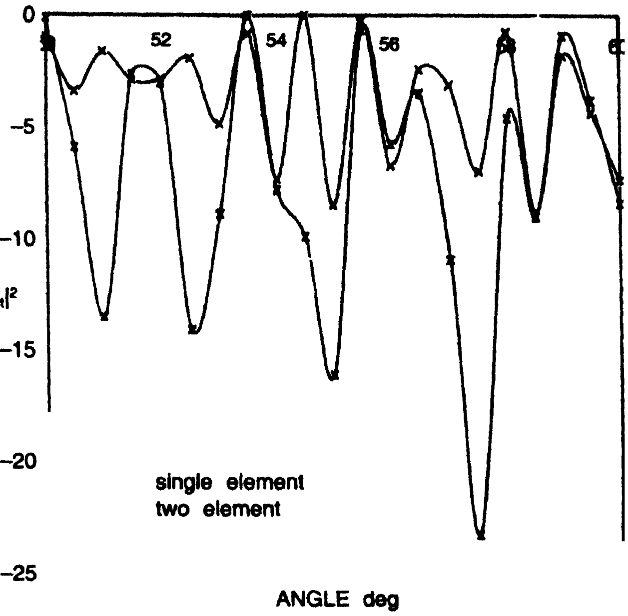

Figure 4. Variation of plasma mode field pattern, $|E_{pt}|^2$ for A = 0.5 (plasma), for single-element and two-element ($\beta_1 = \pi/2$) equilateral triangular patch microstrip antenna.

4. Other antenna parameters

4.1. Radiation conductance :

The total power radiated can be calculated by employing Poynting's theorem and is given as :

$$P_r = (1/2).(1/2).\{\ \mathrm{Re}\textstyle\iint s(E \times H^*).ds\}.$$

The factor 1/2 is due to the fact that the power is radiated through the upper half space only and s is the total spherical surface area.

$$P_r = (1/4).\{\mathrm{Re}\textstyle\iint s(E_\theta H_\phi^* - E_\phi H_\theta^*).ds\}.$$

Thus, The expressions for radiated power in EM- and P-modes are obtained using the relation [6,8] :

$$P_e = (A/4\eta_0).\int_0^{2\pi}\int_0^{\pi}\left\{|E_{\theta t}|^2 + |E_{\phi t}|^2\right\}.r^2.\sin\theta.d\theta.d\phi , \quad (11)$$

$$P_p = (1/2\eta_0).(A/1-A^2).(v/c).$$

$$\int_0^{2\pi}\int_0^{\pi} |E_{pt}|^2 .r^2.\sin\theta.d\theta.d\phi . \quad (12)$$

Here, $A = (1-\omega_p^2/\omega_0^2)^{1/2}$ and ω_p/ω_0 is the plasma to source frequency ratio.

The radiation conductance of an antenna in EM-mode and P-mode can be defined as :

$$G = 2.P_e/V_0^2, \quad (13)$$

$$G_p = 2.P_p/V_0^2. \quad (14)$$

The values of G_e and G_p are computed and plotted in Figures 5 and 6.

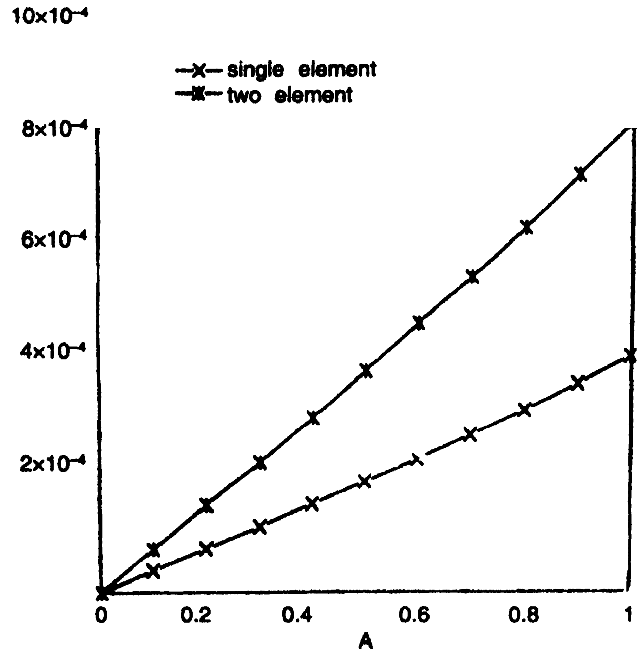

Figure 5. Variation of radiation conductance G_e for EM-mode with plasma parameter A.

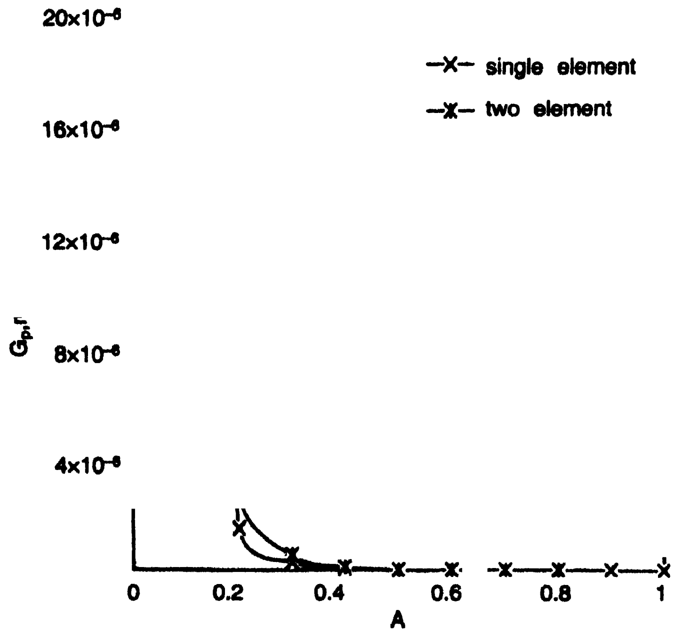

Figure 6. Variation of radiation conductance G_p for P-mode with plasma parameter A.

4.2. *Directivity :*

The directivity of an antenna in a given direction is defined as the ratio of the radiation intensity in that direction to the average radiated power of the antenna. It can be expressed as

$$D_e = 4\pi\{\mathrm{Max}.R(\theta,\phi)\}/\int_0^{2\pi}\int_0^{\pi} R(\theta,\phi).r^2.\sin\theta.d\theta.d\phi, \tag{15}$$

$$D_p = 4\pi\{\mathrm{Max}.R_p(\theta,\phi)\}/\int_0^{2\pi}\int_0^{\pi} R_p(\theta,\phi).r^2.\sin\theta.d\theta.d\phi. \tag{16}$$

The values of D_e and D_p are computed and plotted in Figures 7 and 8.

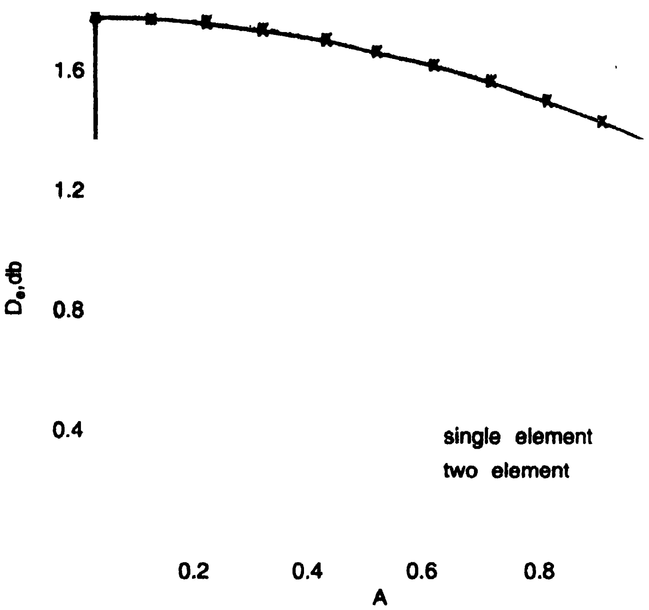

Figure 7. Variation of directivity D_e for EM-mode with plasma parameter A.

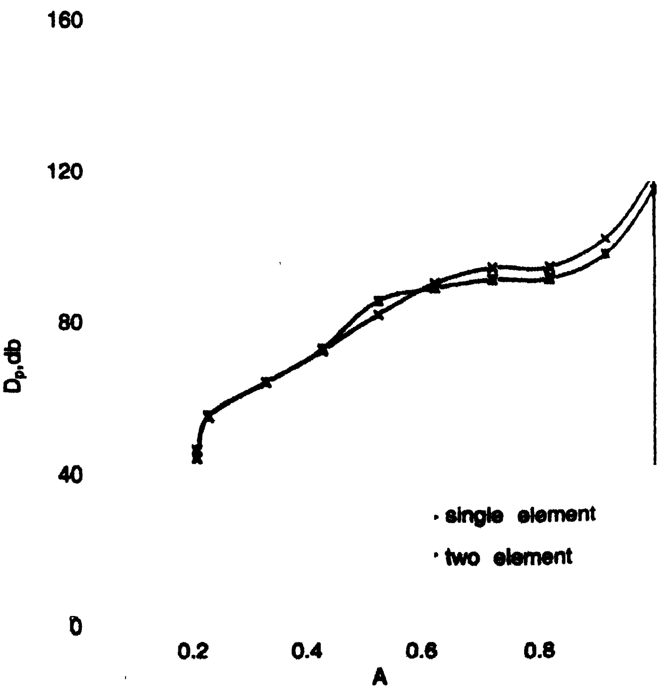

Figure 8. Variation of directivity D_p for P-mode with plasma parameter A

4.3. Quality factor :

A parameter specifying frequency selectivity of a resonant circuit is the quality factor Q, which can be defined as the ratio between energy stored in the system and the energy lost.

The total Q of a microstrip radiating element comprises contributions due to the radiation Q_r, conductor loss Q_c, and dielectric loss Q_d quality factors, so

$$1/Q_t = 1/Q_r + 1/Q_c + 1/Q_d, \tag{17}$$

where $Q_r = \omega_0.Wt/P_r$, $Q_c = \omega_0.Wt/P_c = (\pi f.\mu.\sigma)^{1/2}.h$, $Q_d = \omega_0.W_t/P_d = 1/\tan\delta$.
Here, W_t is the energy stored in the antenna element, P_c and P_d are power loss factors due to the conductors and dielectric, respectively, σ is the conductivity of the conductors.

The energy stored in the triangular radiating element is given by

$$W_t = (\varepsilon h/2).\ \iint |E_z(x,y)|^2.dx.dy. \tag{18}$$

The values of Q_e and Q_p are computed and plotted in Figures 9 and 10.

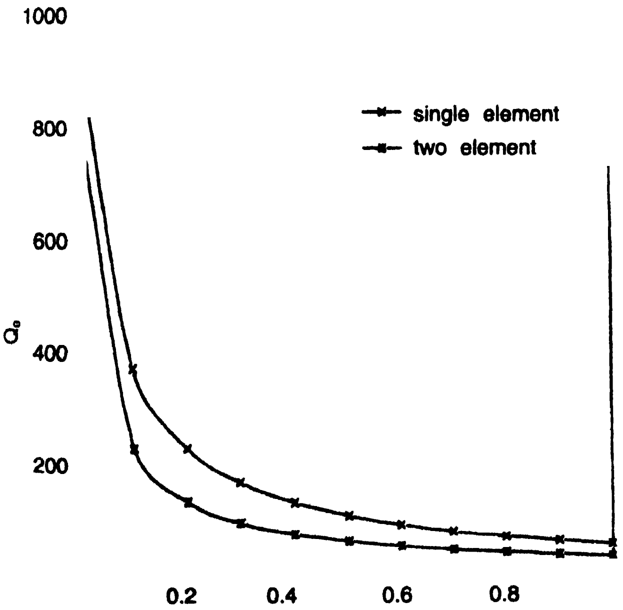

Figure 9. Variation of quality factor Q_e for EM-mode with plasma parameter A.

4.4. Radiation efficiency :

The radiation efficiency of the antenna in plasma medium is defined as :

$$\eta = P_e/(P_e + P_p). \tag{19}$$

The radiation efficiency of single element as well as two element array for different values of plasma parameter A are plotted in Figure 11.

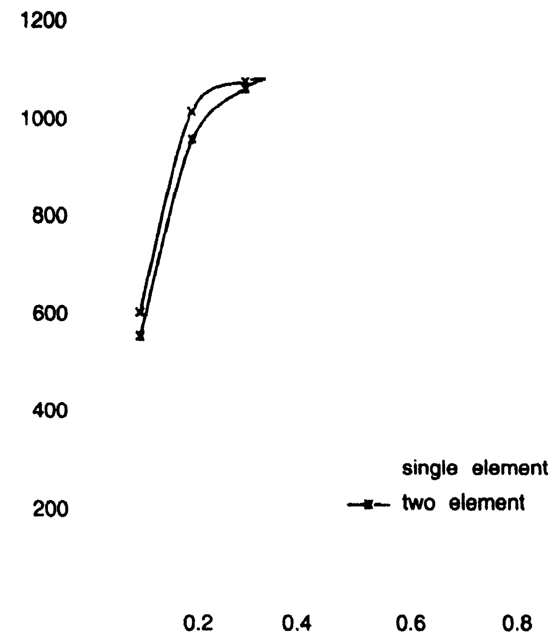

Figure 10. Variation of quality factor Q_p for P-mode with plasma parameter A.

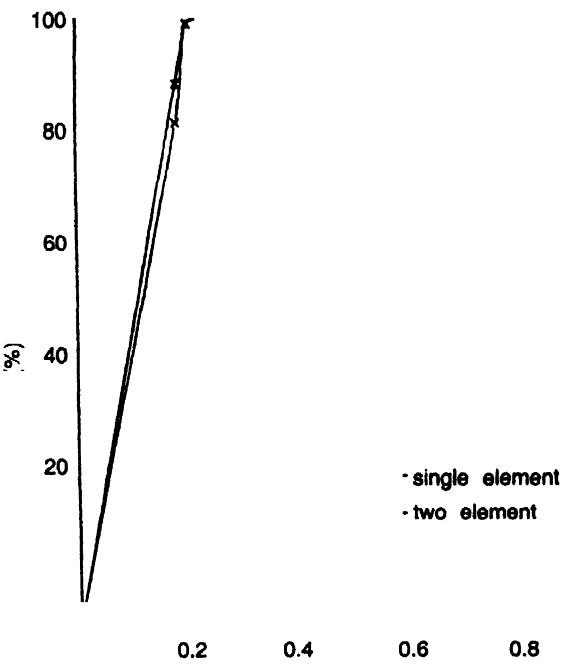

Figure 11. Variation of radiation efficiency η with plasma parameter A.

5. Conclusion

The radiation characteristics of two-element linear array of equilateral triangular patch microstrip antenna have been studied. The results of the array geometry are compared with those of single-element of equilateral triangular patch microstrip antenna. It is found that there is a significant change in the radiation characteristics of array geometry. In case of EM-mode, the shape of the field pattern has been modified to a great extent and redistributes the field intensities considerably. It is also observed that the radiation patterns of a single-element antenna contain only one major lobe of considerably wide beam-width, while the array geometry produces a directive beam with a narrow beam-width. In case of P-mode, the field patterns are similar to single-element microstrip antenna and represent a large number of lobes in a small interval of 10° (from 50° to 60°). It is further observed that the values of radiation conductance are considerably higher for array geometry and it increases continuously with increasing plasma parameter. The values of directivity for array geometry are also considerably higher than that of single-element of equilateral triangular patch microstrip antenna. The radiation efficiency (η) of antenna in plasma medium as a function of plasma parameter A is computed. It is observed from Figure 11 that the radiation efficiency is maximum for higher values of plasma parameter A. For lower values of A, the power contributed by electroacoustic waves is much higher than the useful power contributed by EM waves. Therefore, the radiation efficiency of antenna for lower values of A is sufficiently low.

Finally, it is concluded that two-element linear array of equilateral triangular patch microstrip antenna has unique radiation characteristics and can be employed in applications where high gain and narrow beam-width are required. The results of the present study are useful particularly for space vehicles because such type of array antenna can be mounted on the flat surface as well as on the curved surface of the vehicles.

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